

LLNL Evaluations: ^{239}U , ^7Be , ECPL

CSEWG 2016

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using also evaluations of D. Brown, P. Navratil & C. Hagmann



LLNL-PRES-709980

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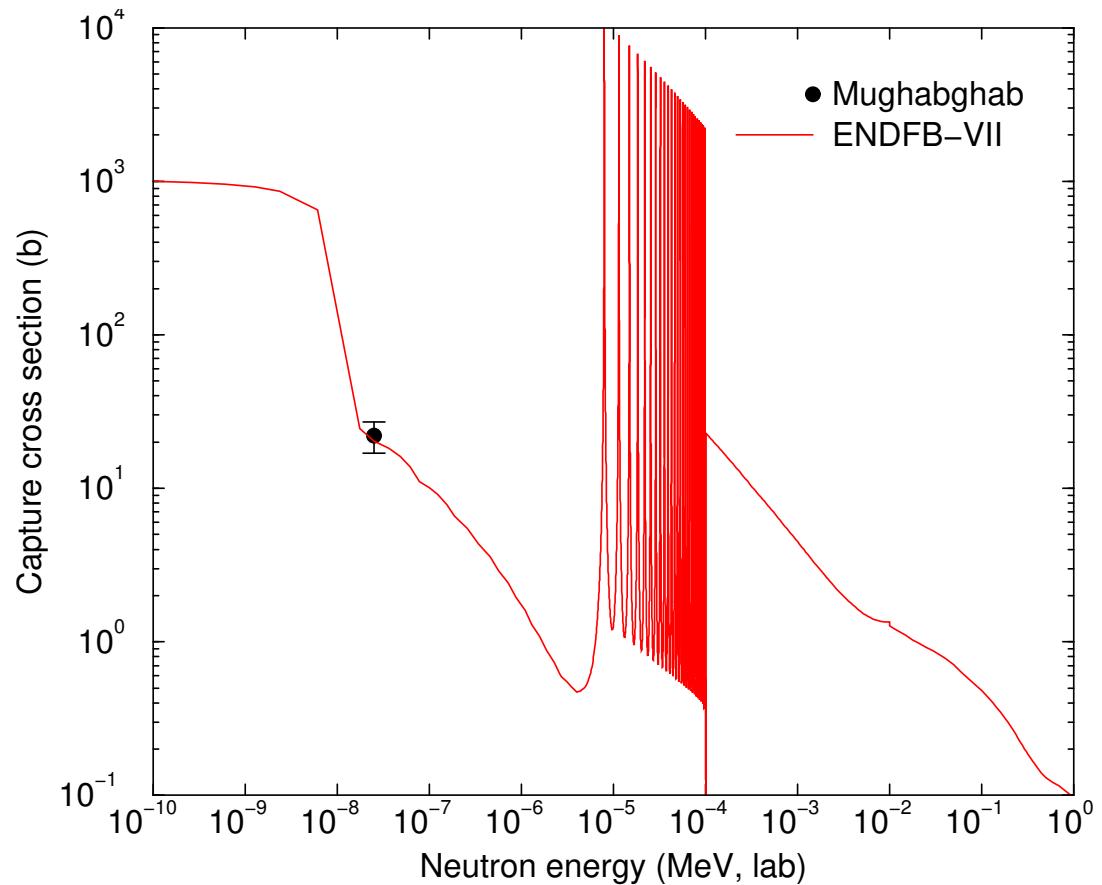


New evaluations from LLNL

- n + ^{239}U : new (full) set of resonances
- n + ^7Be : extend evaluation from 8.1 to 20 MeV
- Charged-particle reactions from ECPL at LLNL:
conversion to ENDF via GND –
 - Elastic only:
 - p + a, t + a, h + a, a + a
 - With also transfers/breakup/charge exchange:
 - p + ^7Li , d + ^7Li , t + ^7Li , h + h

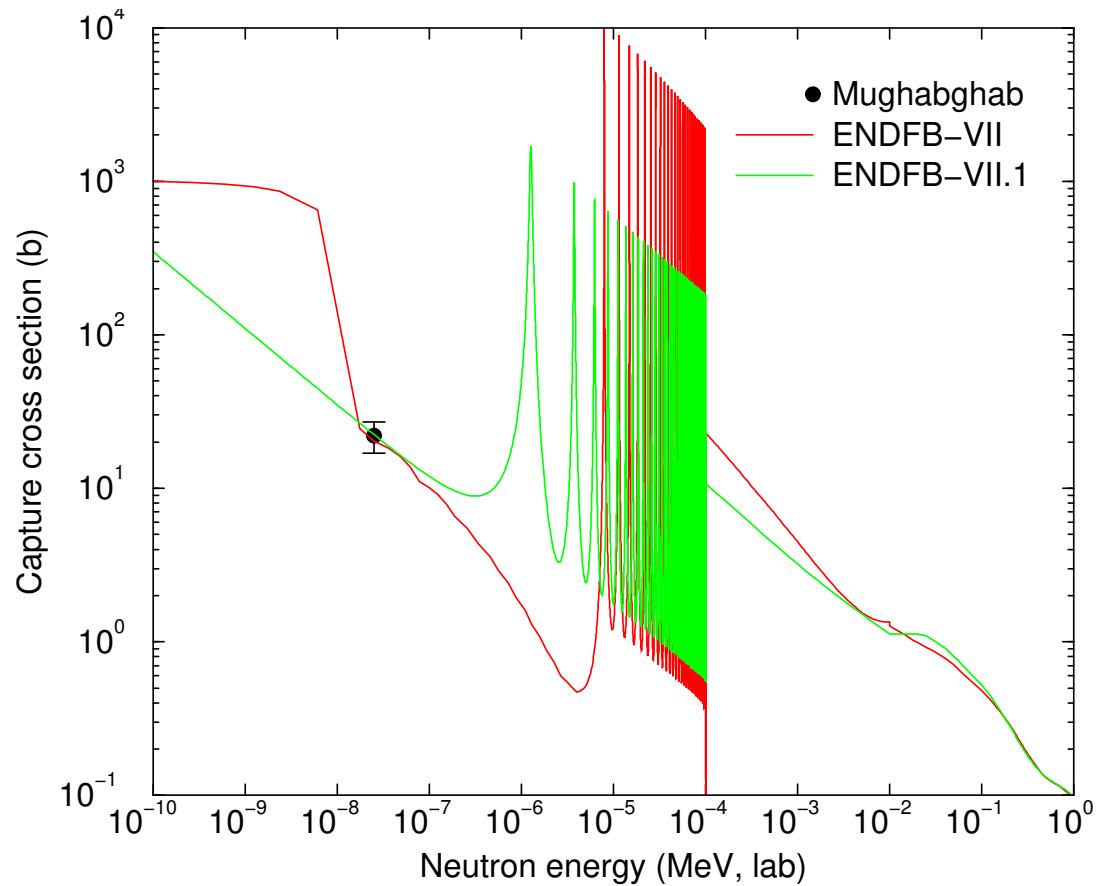
$n + {}^{239}\text{U}$ evaluation 1: History

- ${}^{239}\text{U}$ has half-life of 23 min, so cannot be a good target. Only thermal (n,γ) and (n,f) measured inclusively
 - But is essential step in ${}^{238}\text{U} + n \rightarrow {}^{239}\text{U} \rightarrow {}^{239}\text{Np} \rightarrow {}^{239}\text{Pu}$, so need accurate side-reactions e.g. ${}^{239}\text{U}(n,\gamma)$
- Make new evaluation by copying from ${}^{237}\text{U}$ evaluation & modify
- Make ‘picket fence’ resonances. Spin $5/2^+ * n(1/2^+)$, so $J=2^+$ or 3^+
- ENDF/B-VII from LANL
 - See plot
 - Capture \approx Mughabghab 22 ± 5 b
 - BUT: only $J=1/2^+$ resonances
 - : simplified URR from 10^2 - 10^4 eV.
 - AND: strange bump below thermal



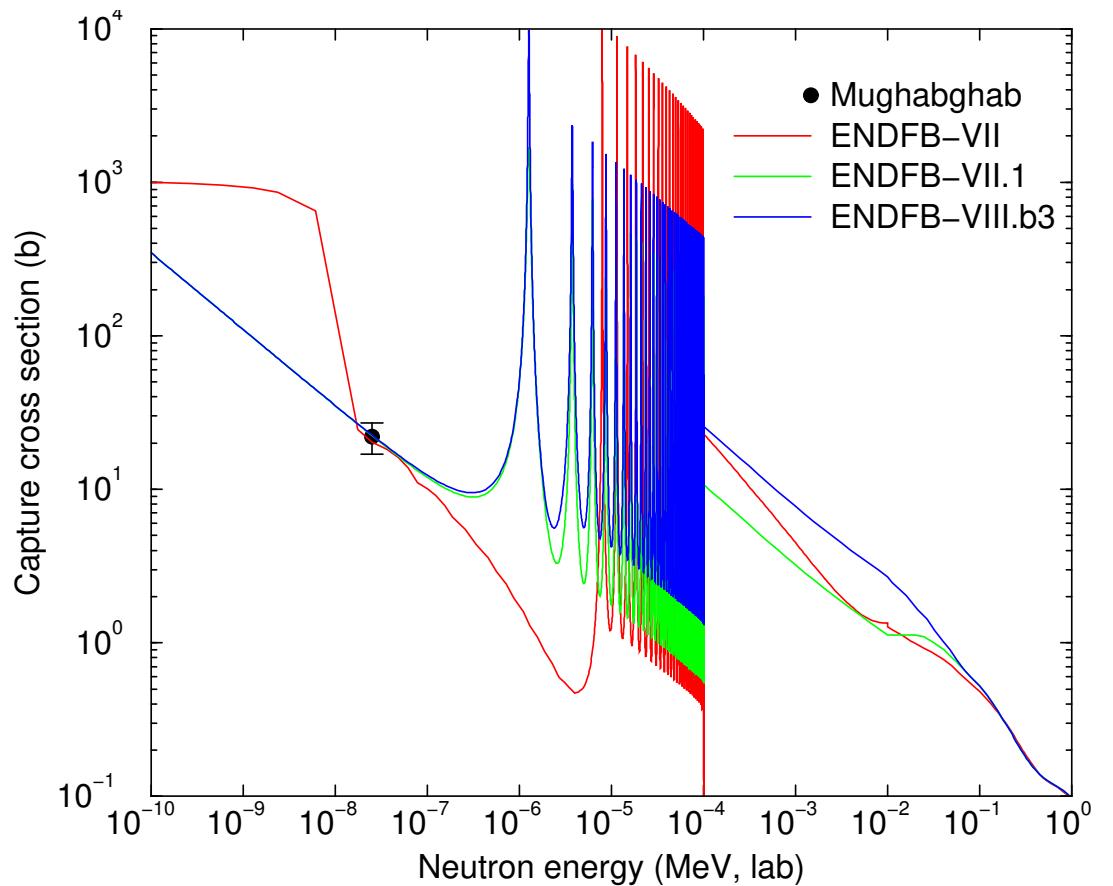
$n + {}^{239}\text{U}$ evaluation 2: History

- ${}^{239}\text{U}$ has half-life of 23 min, so cannot be a good target. Only thermal (n,γ) and (n,f) measured inclusively
 - But is essential step in ${}^{238}\text{U} + n \rightarrow {}^{239}\text{U} \rightarrow {}^{239}\text{Np} \rightarrow {}^{239}\text{Pu}$, so need accurate side-reactions e.g. ${}^{239}\text{U}(n,\gamma)$
- Make new evaluation by copying from ${}^{237}\text{U}$ evaluation & modify
- Make ‘picket fence’ resonances. Spin $5/2^+ * n(1/2^+)$, so $J=2^+$ or 3^+
- ENDF/B-VII.1 from Trkov, Brown
 - See plot
 - Capture \approx Mughabghab 22 ± 5 b
 - BUT: only $J=2^+$ resonances
 - AND: lower in URR (up to 10 keV)



$n + {}^{239}\text{U}$ evaluation 3: New resonances

- ${}^{239}\text{U}$ has half-life of 23 min, so cannot be a good target. Only thermal (n,γ) and (n,f) measured inclusively
 - But is essential step in ${}^{238}\text{U} + n \rightarrow {}^{239}\text{U} \rightarrow {}^{239}\text{Np} \rightarrow {}^{239}\text{Pu}$, so need accurate side-reactions e.g. ${}^{239}\text{U}(n,\gamma)$
- Make new evaluation by copying from ${}^{237}\text{U}$ evaluation & modify
- Make ‘picket fence’ resonances. Spin $5/2^+ * n(1/2^+)$, so $J=2^+$ or 3^+
- ENDF/B-VIII.b3 from LLNL
 - See plot
 - Capture \approx Mughabghab 22 ± 5 b
 - NOW both $J=2^+$ or 3^+ resonances
 - NOTE higher capture up to 60 keV. Closer to original



^{7}Be evaluation: extend 8.1 to 20 MeV

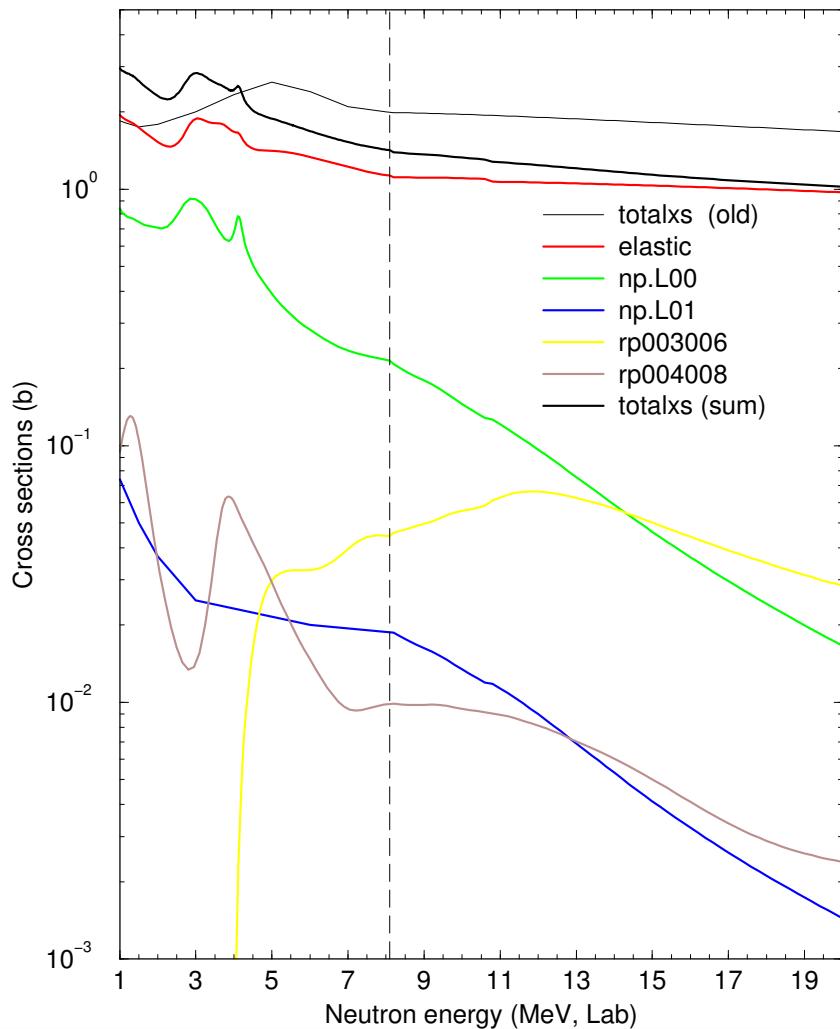
ENDF/B-VII evaluation only extends to 8.1 MeV

ENDF/B-VIII: elastic, (n,p) and (n,α) extended to 20 MeV.

- by rescaling the results of a default TALYS 1.6 calculation (without pre-equilibrium) to match the previous curves at 8.1 MeV.

- Total resummed.

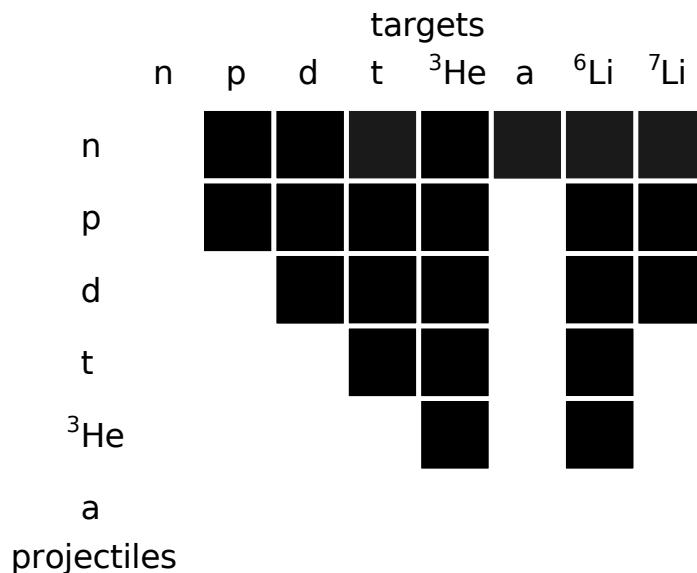
Better than straight lines.



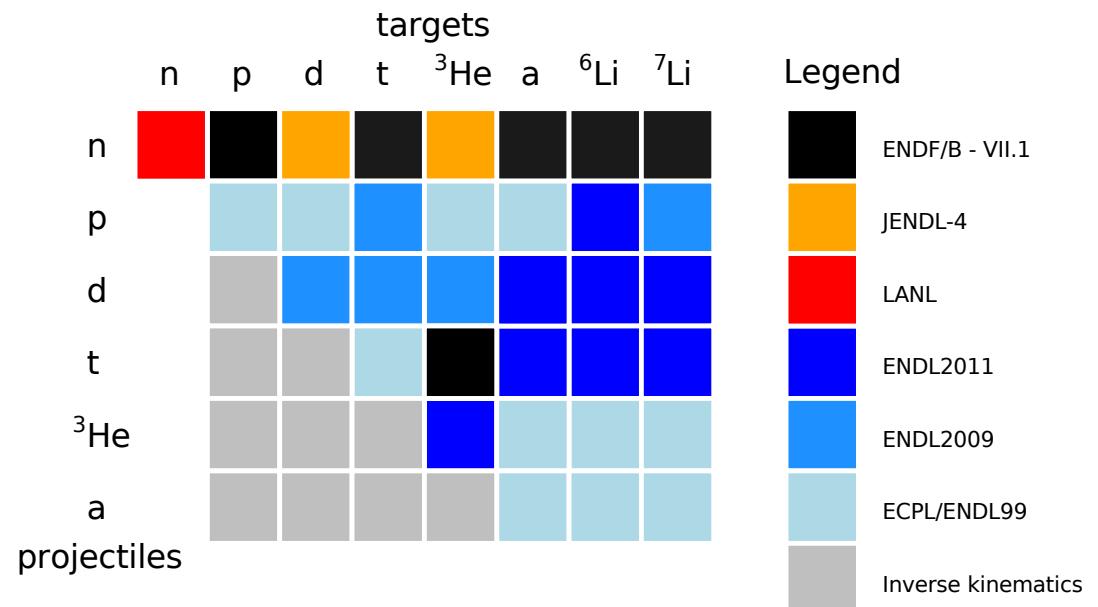
ECPL: ‘Evaluated Charged-Particle Library’ A Thermonuclear Reaction Library

- Legacy ECPL/ENDL99 evaluations
 - Incident charged particles (p,d,t,He3,He4), light targets Z<=3 (p,d,t,He3,He4,Li6,Li7)
 - R.M. White, D.A. Resler, S.I. Warshaw 'Evaluation of Charged-Particle Reactions for Fusion Applications,' Proc. from Nuclear Data for Sci. and Tech., Ed. S.M. Qaim, Juelich, Fed. Rep. Germany, 13-17 May (1991)
 - S.T. Perkins, D.E. Cullen, 'Elastic Nuclear plus Interference cross sections for light-charge particles' Nucl. Sci. Eng. 77, 20-39 (1981)
- New evaluations at LLNL by Petr Navratil, David Brown & Chris Hagmann
 - Main sources for new evaluations
 - Descouvemont R-Matrix analysis
 - P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam, Atomic Data & Nucl. Data Tables 88, 203 (2004)
 - NACRE (Nuclear Astrophysics Compilation of REaction rate)
 - C. Angulo et al., Nucl. Phys. A656 (1999)3-187
 - Experimental data not in EXFOR
- LANL n+n evaluation by Gerry Hale
- JENDL-4 n+d, n+He3 evaluations
- Inverse kinematics used for remaining evaluations

Evaluations in ENDF/B-VII.1



Evaluations in ENDL2011.0



Awaiting LCT=4 option, in October 2016 submitted from LLNL the ENDF files for a+a, d+ ^7Li , h+h, h+a, p+a, p+ ^7Li , t+a, t+ ^7Li

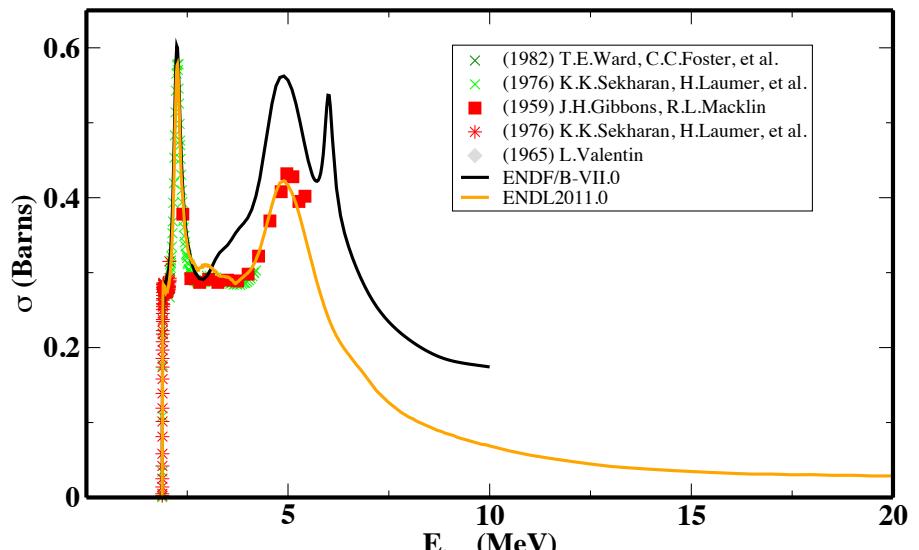
First Tranche of ENDL evaluations

- Following slides list the ENDL evaluations, highlight differences with ENDF
- Simplest evaluations first
 - Proposed ENDF format LCT=4 needed for 2-step decays via resonances in residual nuclei. These later!
- Now elastic only:
 - p + a, t + a, h + a, a + a
- With also transfers/breakup/charge exchange:
 - p + ${}^7\text{Li}$, d + ${}^7\text{Li}$, t + ${}^7\text{Li}$, h + h

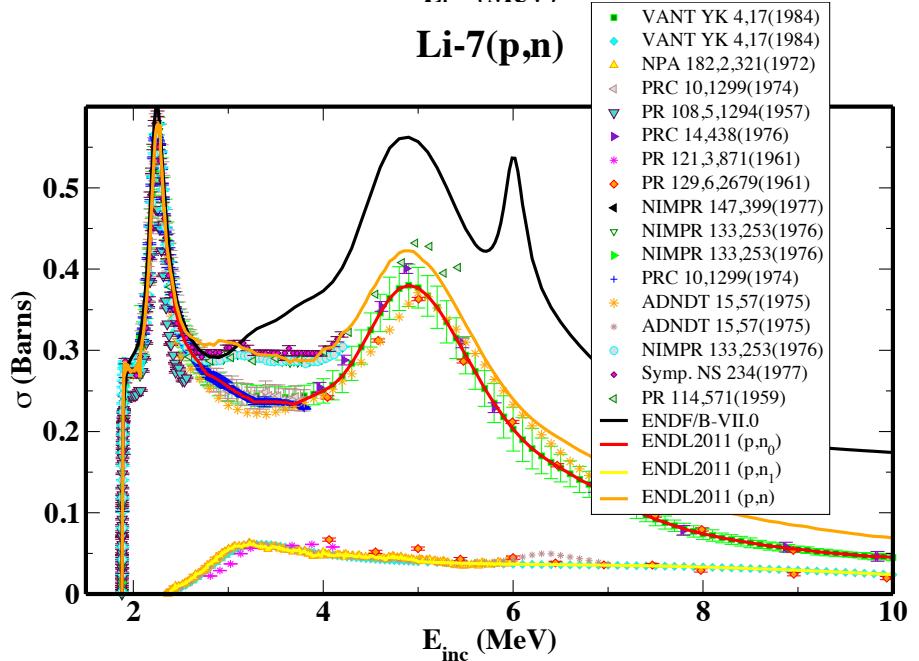
p+Li7 evaluation

- ENDF/B-VII.1 (Page 2004)
 - (p,el) , (p,n'_0) , (p,d_0) , (p,a_0)
- ENDF/B-VIII.b3 (ENDL2011, Navratil 2008)
 - ${}^7\text{Li}(p,n)$
 - Both ECPL and ENDF/B-VII.0 cross-sections were discarded. Evaluation is based purely on data
 - (p,n_0) [ground state]:
 - NIMPR 133, 253 (1976) for 0-2.35 MeV
 - PRC 10, 1299 (1974) for 2.4-3.6 MeV
 - VANT YK 4, 17 (1984) for 3.6-25 MeV
 - PRC 14, 438 (1976) for 25-26 MeV
 - Datasets matched with splines.
 - (p,n_1) [0.4291 MeV excited state]:
 - NPA 182, 2, 321 (1972) for 2.3-5 MeV
 - VANT YK 4, 17 (1984) for 5-25 MeV
 - PRC 14, 438 (1976) for 25-26 MeV
 - Datasets matched with splines
 - Angular distributions
 - Taken from Page's ENDF/B-VII.0 evaluation
 - Distribution for excited state is same as ground state, but threshold is shifted.

Li-7(p,n)

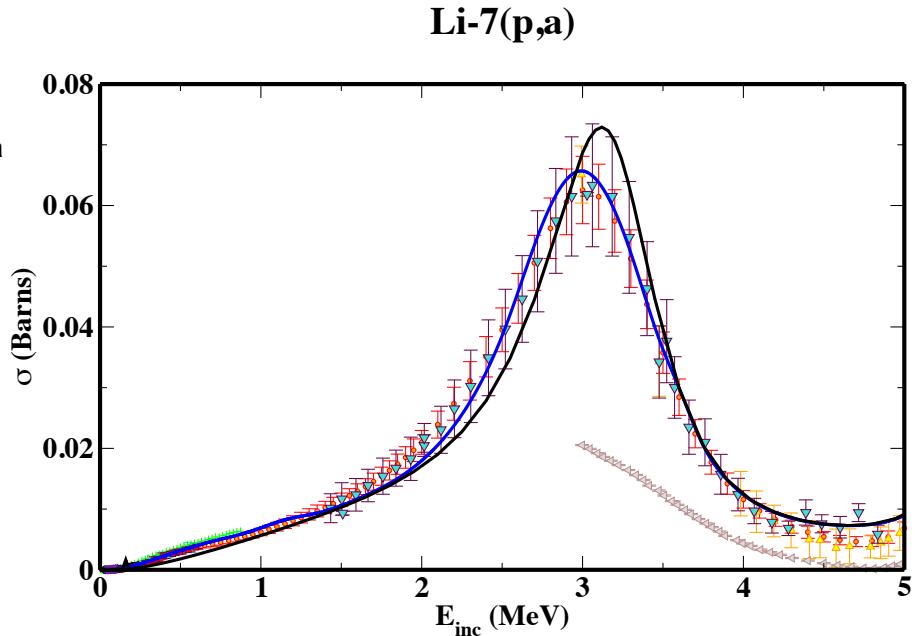
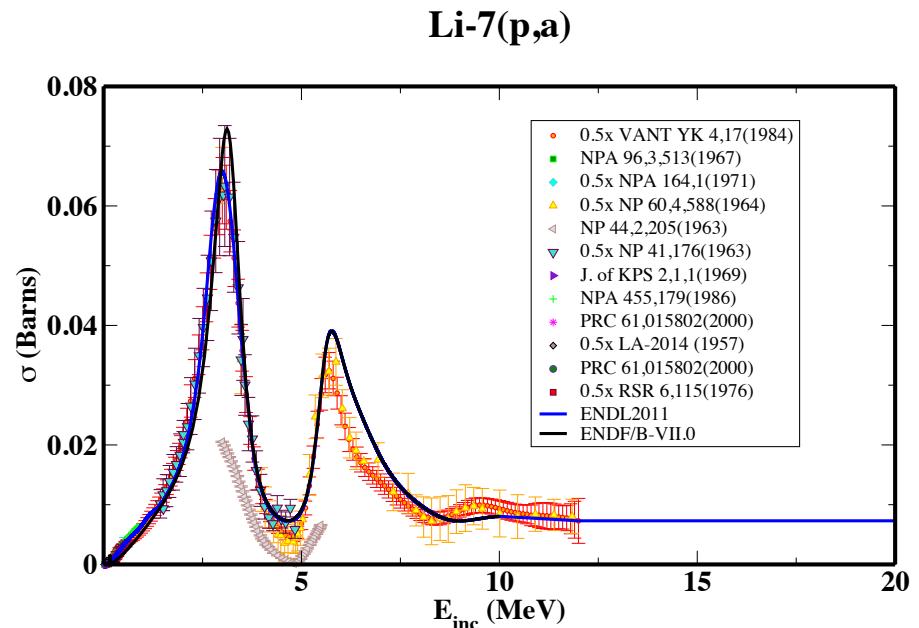


Li-7(p,n)



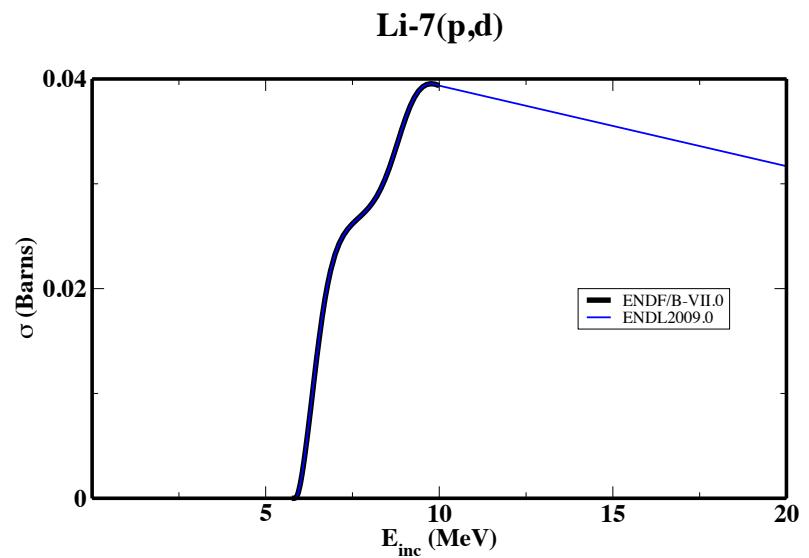
p+Li7 evaluation

- ENDF/B-VII.1 (Page 2004)
 - (p,el), (p,n'0), (p,d0), (p,a0)
- ENDF/B-VIII.b3 (ENDL2011, Navratil 2008)
 - (p,el) from ECPL
 - (p,a)
 - Cross-section
 - < 2.6 MeV : Descouvemont [3] S-factor
 - 2.6 - 3.15 MeV : three experimental points from the Rice measurement
 - > 3.15 MeV : Page evaluation
 - Note EXFOR file with the NP 33, 449 (1962) data is wrong as there was an erratum in NP 41, 176 (1963) (data needs to be multiplied by 10/7), divided by 2 as normalization based on 1958 measurement that counted alphas
 - Angular distributions from ENDF/B-VII.0
- Decouvement 2004
 - [3] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam, Atomic Data and Nuclear Data Tables 88, 203 (2004).



p+Li7 evaluation

- ENDF/B-VII.1 (Page 2004)
 - (p, el) , (p, n'_0) , (p, d_0) , (p, α_0)
- ENDF/B-VIII.b3
(ENDL2009, Navratil 2008)
 - ${}^7\text{Li}(p, d)$
 - Cross-section
 - < 10 MeV from ENDF/B-VII.0
 - To extrapolate to 30 MeV, integrated the cross section from Fig. 6 of PR 163,4,1066 (1967) and got 24 mb. Measurement was at 33.6 MeV proton energy. Recommend to use 24 mb at 30 MeV and make a linear interpolation to the 10 MeV point of Page
 - Angular distributions from ENDF/B-VII.0

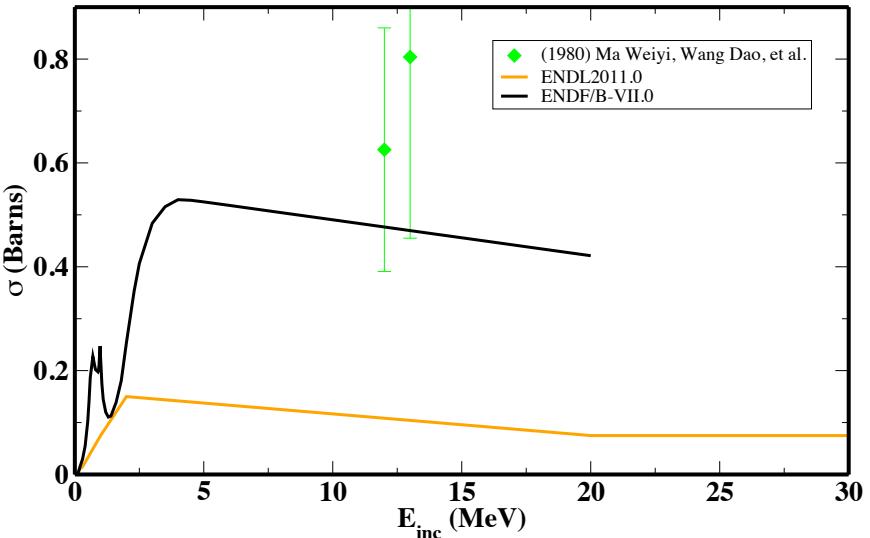


d+Li7 evaluation

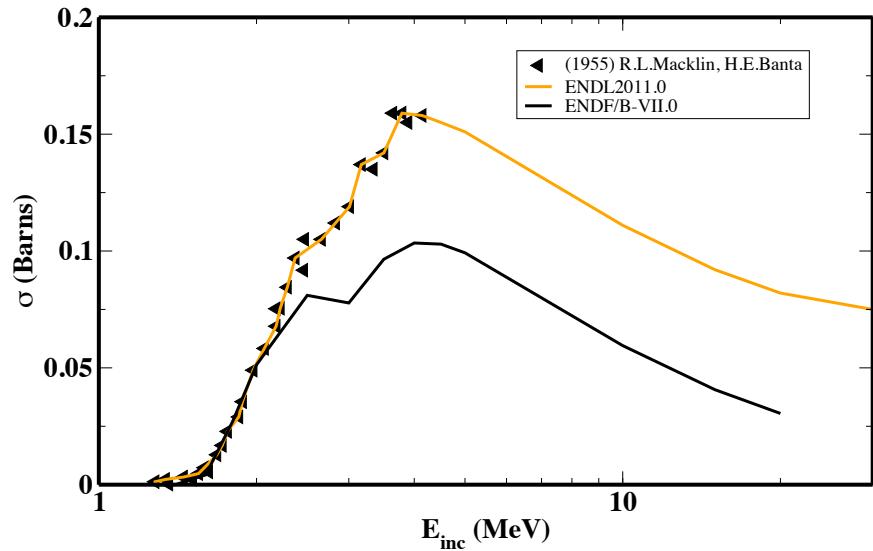
- ENDF/B-VII.0 (Hale 2003)
 - (d,el), (d,na), (d,t₀)
- ENDF/B-VIII.b3
(ENDL2011.0, Navratil 2010)
 - (d,el) from ENDF, extended up to 30 MeV
 - (d,na) from ECPL (but ENDF better fit to data)
 - (d,t) from R.L. Macklin [5] data up to 4 MeV; at higher energies scaled ENDF
 - Angular distributions: ENDF/B-VII.0

[5] R.L. Macklin, H.E. Banta, Phys. Rev., 97, 753 (1955)

Li-7(d,n+a)



Li-7(d,t)

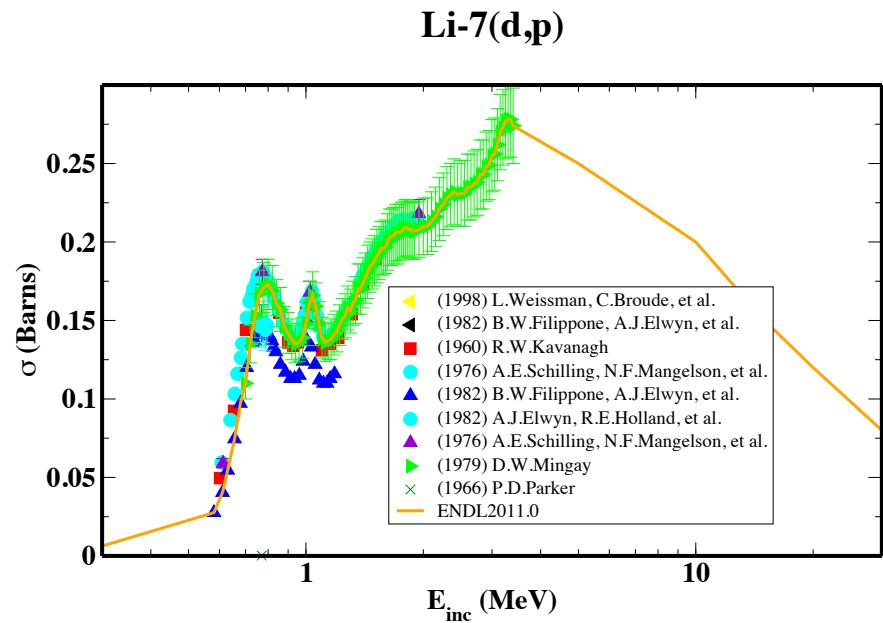
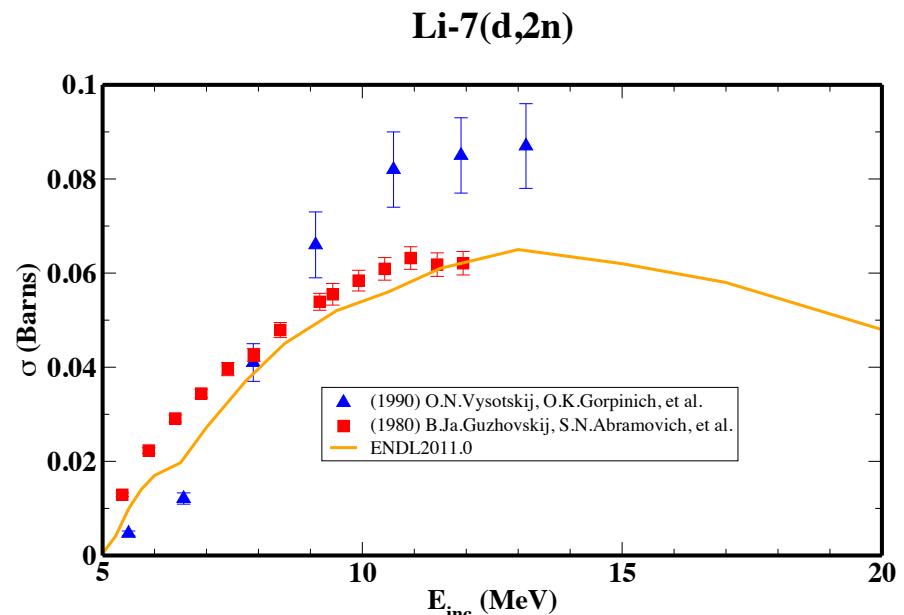


d+Li7 evaluation

- ENDF/B-VII.0 (Hale 2003)
 - (d,el), (d,na), (d,t₀)
- ENDL2011.0 (Navratil 2010)
 - (d,2n) from ECPL
 - (d,p)
 - < 0.7 MeV from Ref. [3]
 - 0.7 - 3.4 MeV from Ref. [4]
 - > 3.4 MeV educated guess
 - Angular distributions: from (d,na) neutron dist.

[3] B.W. Filippone, A.J. Elwyn, W. Ray Jr., D.D. Koetke, Phys. Rev. C, 25, 2174 (1982)

[4] D.W. Mingay, J. SAP, 2, (3), 107 (1979)

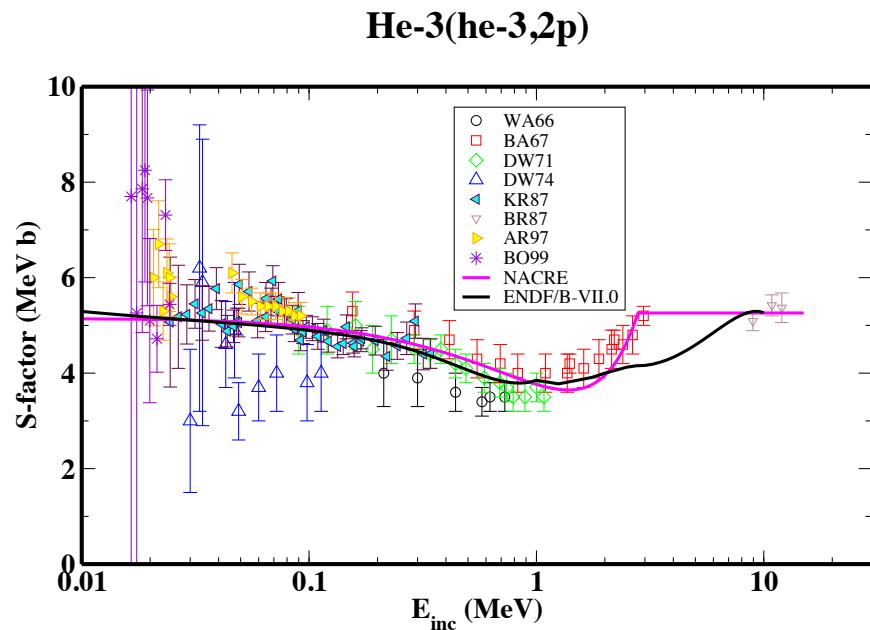


He3+He3 evaluation

- ENDF/B-VII.0 (Hale 2001)
 - (He3,el), (He3,2p)
- ENDF/B-VIII.b3
(ENDL2011.0, Navratil 2010)
 - (He3,el) from ENDF
 - (He3,2p)
 - NACRE S-factor evaluation [4] that includes LUNA data [5]
 - Angle and energy distributions: from ENDF

[4] C. Angulo et al. (NACRE Collaboration), Nucl. Phys. A656 (1999)3-187

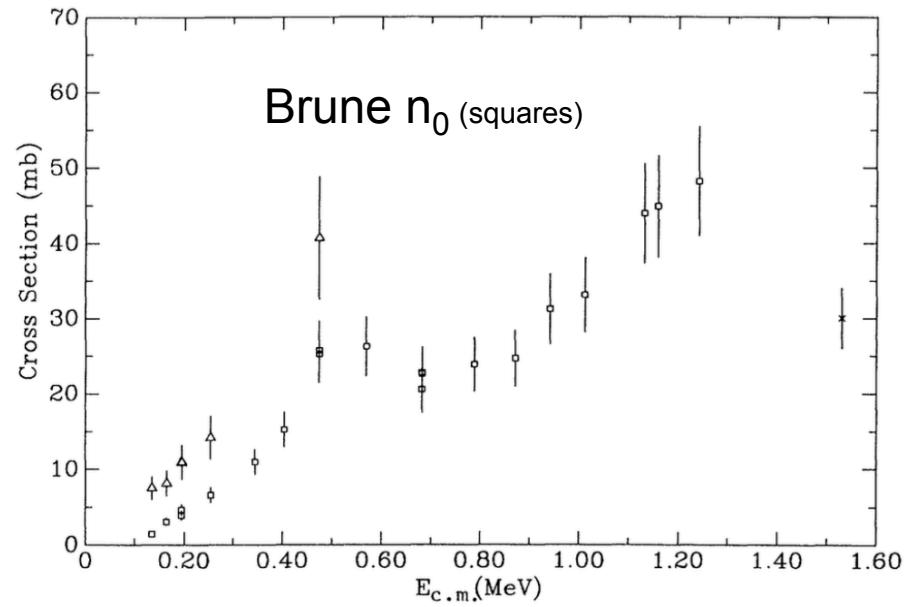
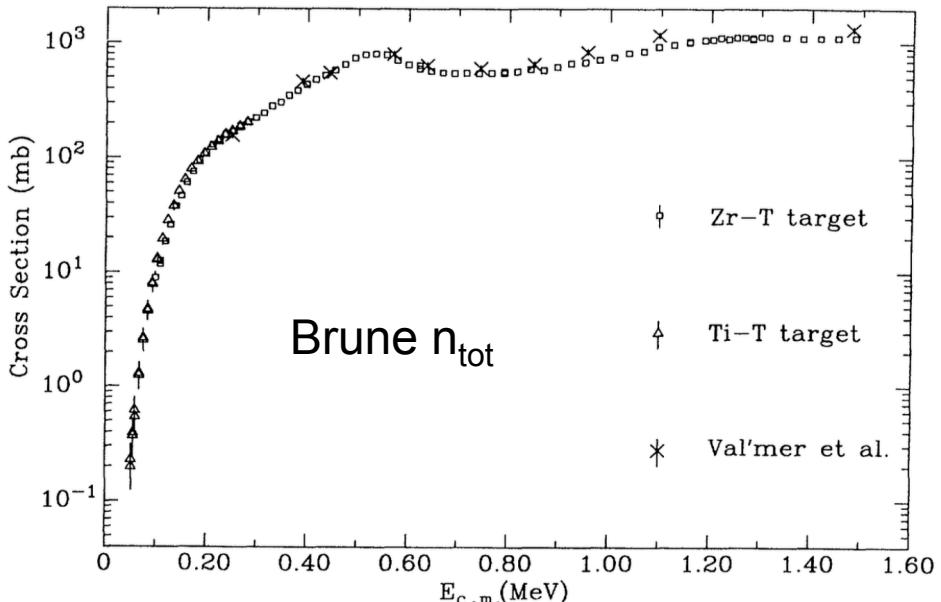
[5] The LUNA Collaboration, M. Junker, et al., The cross section of ${}^3\text{He}({}^3\text{He},2\text{p}){}^4\text{He}$ measured at solar energies, Nuclear Physics B - Proceedings Supplements, Volume 70, Issues 1-3, Proceedings of the Fifth International Workshop on topics in Astroparticle and Underground Physics, January 1999, Pages 382-385, ISSN 0920-5632.



t+Li7 evaluation

- Dispute over channel $^7\text{Li}(t,n)^9\text{Be}$ in competition with $^7\text{Li}(t,n)\alpha\alpha$ using results from Brune et al [1]
- Channels: n_0 and n_{tot} – endf MT=50, 24 or endl c=11, 33
- Problem: Fig 9 (above) for n_{tot} used for n_0 in LLNL evaluations since 1999. Should be Fig 7 (below).
- We needed to re-evaluate this cross section!

[1] C. R. Brune et al, Phys. Rev. C **43**, 875 (1991)

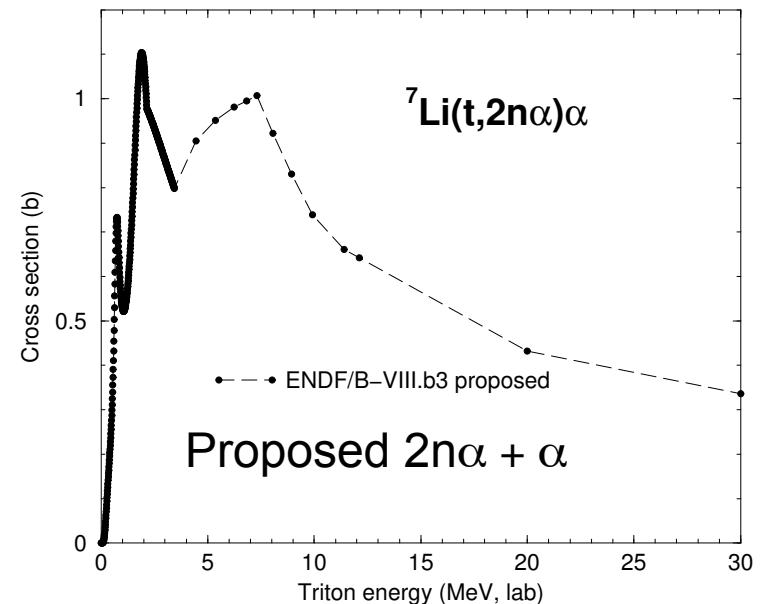
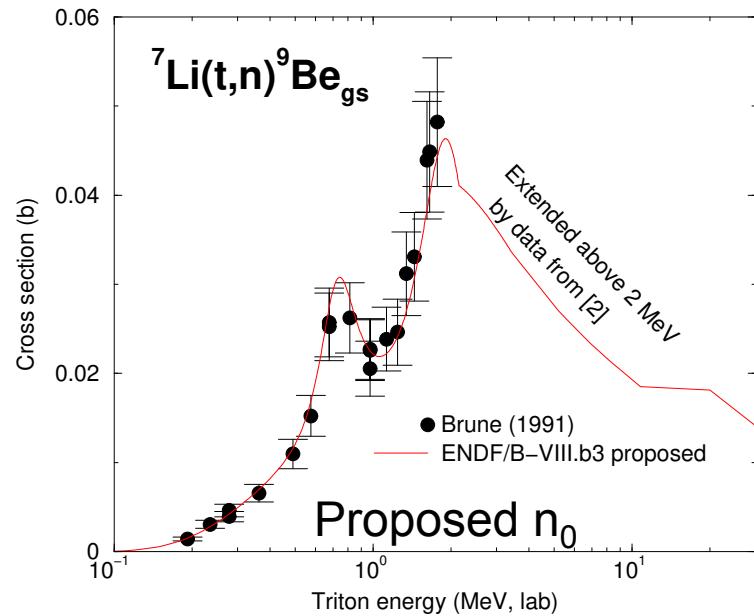


t+Li7 evaluation

- Inverse reaction ${}^9\text{Be}(n,t){}^7\text{Li}$ has been measured [2], and can confirm the n_0 cross section to the ground state.
- Also use data of [2] to extend Brune data to higher incident energies.
- Extra cross section ($n_{\text{tot}} - n_0$) moved to $2n\alpha$ inclusive channel (MT=24, c=33).

[1] C. R. Brune et al, Phys. Rev. C **43**, 875 (1991)

[2] F.S. Dietrich et al, Nucl. Sci. Eng. **61**, 267 (1976).



Translation from ENDL to ENDF

- New LLNL evaluations developed using ENDL format from variety of sources
- When translating from ENDF into ENDL, information was lost
 - Reformatted ENDF parameterized forms to pointwise data for ENDL
 - such as phase space representation
 - Rebuild evaluations in ENDF format using GND/fudge to do this.
- Here are first evaluations built using new fudge/GND
 - Develop framework in fudge for cut/paste evaluations from different sources
- Documentation needs to be re-written for all evaluations
 - Currently too much ENDL speak

Future for cp evaluations

- All the charged-particle evaluations here are over 5 years old
 - Delays to ENDF from GND and ENDF format changes (still underway for two-step decays)
- Future evaluations can & will be full R-matrix calculations, at least up to energies of statistical models
 - No cp R-matrix parameters in ENDF yet
 - Need to extend ENDF infrastructure (GND, PREPRO) for cp reconstructions!
 - Consistent cross sections and angular distributions
 - LANL, LLNL, Notre Dame, ORNL evaluations underway
 - Needed for astrophysics, fusion, and ion-beam analysis.
 - Consultants' meetings at IAEA on R-matrix Data and Codes (Dec 2015 and Dec 2016)
 - I foresee many R-matrix fits for cp on targets up to $A \lesssim 40$
- Still need R-matrix developments for
 - Two-step decays (Hale and Brune demonstrate for $t+t \rightarrow {}^5\text{He}^* + n$)
 - 'Democratic breakup' (discretized continuum) [Sofia Quaglioni at LLNL]
 - Especially if future formats can describe exit correlations.



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